Understanding uncertainties in energy production estimates for offshore wind farms

J.L. Phillips*, C.A. Morgan , J. Jacquemin

Garrad Hassan and Partners, Bristol, UK

Abstract

Significant uncertainty and risk is associated with availability performance and O&M costs for offshore wind projects. This is largely the result of a lack of commercial experience within the offshore wind industry. In contrast, the operation of onshore wind farms is now relatively well understood, this being the result of experience gained over many years of commercial deployment. Specifically, limited access and uncertain costs are two issues which must be tackled during the development of an offshore wind project. To support this process, a simulation modelling tool has been developed which can be used to estimate wind farm performance, optimise O&M strategies and examine key operational risks on a site-specific basis. This tool is based on time domain Monte-Carlo simulation with turbine failures and weather conditions being stochastic variables. Deterministic model inputs comprise environmental and infrastructure constraints and underlying assumptions on the behaviour of service crews. Operational simulations can be run for many years during which important performance parameters are recorded. The model has been applied to a notional offshore wind farm, in order to demonstrate the role such an approach can provide as part of a risk assessment or O&M optimisation exercise.

Keywords: Offshore wind farms; Risk; Availability; O&M modelling.

* *Corresponding Author. joe.phillips@garradhassan.com DDI + 44 (0) 117 972 9723*
Garrad Hassan and Partners, St Vincents Works, Silverthorne Lane, Bristol. BS2 0QD. UK

1. Introduction

The development of offshore wind energy technology presents industrialised nations with a significant opportunity to mitigate greenhouse gas emissions in accordance with national or international climate change commitments. The potential for this technology in Europe has recently been estimated[1] with a postulated market projection of over 20 GW by 2010. In order to realise this potential, technological and policy lessons can be learned from experience with *onshore* wind projects. However, clear distinctions must be drawn between the two technologies and offshore-specific challenges must be investigated and understood fully.

While a "learning by doing" approach is likely to be of significant benefit to all industry players as experience is accrued, many of the more important technical risks associated with operational aspects of offshore wind, may be examined immediately through simulation modelling.

1.1 Onshore experience

One of the most important risks associated with the development of onshore wind farms has been that associated with the predicted long-term wind resource and energy production. These so called "wind risks" may be reliably quantified if high quality onsite measurements are conducted and a suitable source of long-term reference data is available. A recent validation study of predictions made by Garrad Hassan and Partners[2] showed that both central (P50) and downside (P90) energy estimates can be quantified accurately, if rigorous methodologies are applied. Figure 1 below shows the headline results from this work, the validation database comprising 298 wind farm years. On average, annual production is 97 % of the GH central estimate which, given the limitations of the validation exercise represents a good level of overall agreement.

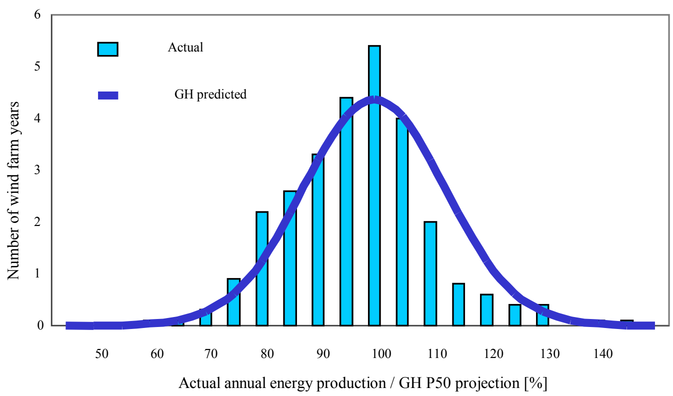

Figure 1: Distribution of annual production relative to Garrad Hassan projected central estimates

Some of the most important sources of uncertainty associated with long-term onshore energy predictions are listed below;

- Measurement accuracy;
- Data correlation uncertainty;
- Historical wind variability;
- Future wind variability;
- Wind flow modelling.

In the absence of topographic effects, the latter of these factors can be largely mitigated for offshore projects, if a high quality onsite measurement campaign is implemented. In contrast, a notable omission from this list is a factor which has much more significance in the offshore case; that of operational uncertainty.

The past two decades has provided the wind industry with a wealth of operational experience. A modern wind farm comprising turbines of proven reliability can expect to achieve an availability of 97 % or better[3, 4].

This onshore experience cannot be directly translated for offshore wind projects, due to the increased significance of turbine access incurred by adverse weather conditions. In addition, the impact of site-specific factors on the cost of offshore servicing and repair operations is poorly understood.

1.2 Offshore operational risks

In the early years of wind farm operation, operational risks can be controlled to some extent through the provision of a warranty agreement between the owner and turbine supplier. However, such risks must also be considered for the post-warranty period and an assumption for the projected long-term availability of the wind farm is usually required for project finance. Even during the warranty period, current trends suggest that it will be the wind farm owner who owns most, if not all of the non-access or "weather" risk and hence such warranties do not mitigate the full range of operational risk.

In the absence of a significant quantity of commercial experience, the offshore wind industry must investigate operational risks differently. A simulation modelling approach is presented in this paper, which may be adopted to support offshore O&M decision making at each stage of the project life.

2. Modelling offshore O&M

A computer model, known as O2M ("Optimisation of Operations and Maintenance"), has been developed to simulate the operation of an offshore wind farm. It is based on work conducted by Bossanyi and Strowbridge[5, 6] during the early phases of onshore wind deployment in the UK.

The model is run forward in the time domain, the overall approach being based on Monte Carlo simulation, with turbine failures occurring on a stochastic basis. Delays associated with poor weather are simulated using a statistical wave module, driven by spectral analysis of the long-term wave climate at the site of interest.

Figure 2 shows a simplified block diagram of the O2M model.

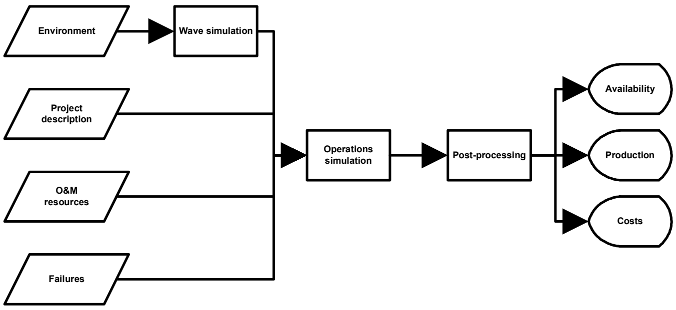

Figure 2: Simplified block diagram of the O2M model structure

There follows a more detailed description of the model structure.

2.1 Input data and assumptions

The main environmental input dataset comprises a timeseries of Significant Wave Height (Hs), ideally gathered at the wind farm site itself. These data are used to represent the long-term wave climate and so should cover the longest possible period, preferably several years. The process by which these data are then synthesised to form a much longer timeseries of Hs is described below in Section 2.2.

The relationship between Hs and wind speed is also an environmental input consideration. A description of this relationship allows the effect of poor wind farm accessibility during periods of high wind to be captured in the calculation of lost revenue.

The wind farm project itself must also be described. The number of turbines, stores location, service base location, mobilisation times and travel times are defined as input data to the O2M model. Also required is a prediction of the idealised long-term net energy output of the wind farm, neglecting availability losses and broken down by month. This seasonal breakdown is also required in order to model the "high wind - low access" effect described above.

The model is also capable of simulating the operation of multiple wind farm sites, serviced from a common base and parts store. This capability has not been implemented for the purposes of the current study.

The O&M resources available to the wind farm comprise the service crews, access vessels and spares holding facilities. Staffing inputs include the number of crews, their associated cost, shift rota and working days per week. In addition to the transit speed, which is inherently defined by the transit time between locations, the turbine access method is defined by a limiting Hs and wind speed level for safe turbine access. Spare parts are associated with turbine failure modes and each part has a cost, nominal spares holding level and re-order lead time.

A schedule of turbine failure modes is required as a model input. This schedule is of critical importance to the model operation and output since it comprises the turbine reliability projection and maintenance requirements.

The failure mode schedule includes as many modes of failure as is felt appropriate for the turbine model under consideration. For each mode, the following criteria are defined; Mean Time Between Failure (MTBF), Direct Time To Repair (DTTR) and spare part required.

In addition, the scheduled maintenance requirements of the turbines under consideration form an important input. The minimum and maximum service interval and the duration of each service in crew-hours is defined.

Inherent assumptions in the O2M model govern the status and behaviour of all system elements; turbines, crews, parts and spares. The most important examples of these include;

- Repairs take precedence over scheduled maintenance;
- Crews cannot be deployed when weather access limits are exceeded;
- Repairs and scheduled maintenance activities are interrupted by worsening weather conditions;
- Faults are not diagnosed until a crew has visited the turbine in question;
- Repairs can only commence if the appropriate spare part is available and has been picked up from the parts store;
- If a repair is not finished by the end of a crew's shift, the job will be continued when the next crew comes on shift, if they are available and access is possible;
- As soon as a spare part is taken from the store, a replacement is ordered.

A description of the way in which these assumptions are implemented during the model simulation is provided below in Section 2.3.

2.2 Synthesis of wave data

The analysis of timeseries measurements of wave height at a specific offshore site can allow statistical characterisation of the wave climate during the data collection period. Perhaps the most widely used and from an access point of view, important of these parameters is Significant Wave Height (Hs). However, onsite measurements, if available, generally cover a relatively short period - typically of less than 3 years.

Given measurement constraints, a synthesis approach has been adopted, based on spectral analysis. This approach has three distinct advantages. Firstly, a time series of wave height can be generated which is equal in duration to the conducted simulation, which may be in excess of 100 years. This avoids the need for timeseries repetition. Secondly, such an approach allows Hs to become a fully stochastic element, which more realistically reflects actual operation. That is, the timeseries of Hs is generated on a pseudo-random basis, reflecting the actual variability of sea conditions for a given site. Thirdly, Hs persistence characteristics are captured in the spectral analysis, allowing the generation of realistic site-specific weather windows in the simulation.

Spectral analysis assumes that a signal can be considered as a combination or superposition of a large number of regular sinusoidal wave components with different frequencies, amplitudes, and directions. This is a valid assumption in wave analysis since sea states are in fact composed of superimposed wave components, generated in different regions of the ocean and having propagated and combined to form complex waves at the point of interest.

The wave synthesis module of the O2M model performs the spectral analysis in 2 stages. Firstly, a Fast Fourier Transform (FFT) is performed on the input timeseries of Hs measurements. This results in a wave climate spectrum, an example of which is presented in Figure 3. Frequencies of the highest amplitude in the resultant spectrum denote particularly energetic components of the Hs timeseries. Two examples of this are high-lighted in Figure 3; tidal (dotted circle) and seasonal (solid circle) variation. These deterministic frequencies are identified in the spectrum and their phasing is locked for the synthesis of new Hs data.

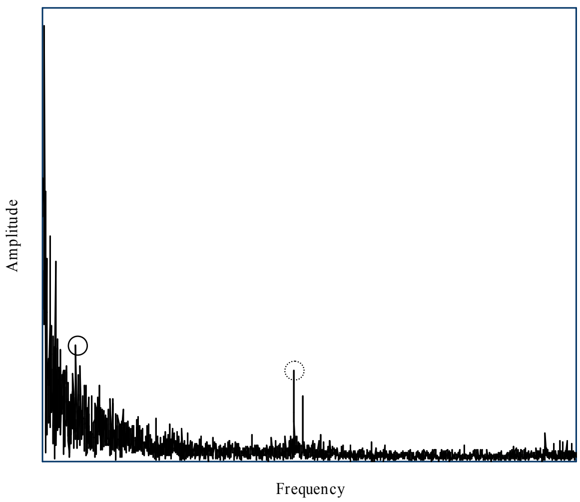

Figure 3: Example output wave climate spectrum from FFT process

The second stage involves the synthesis of the new Hs timeseries. This is implemented through an inverse FFT process, conducted with a random phase angle. The phase angle is applied to all frequencies other than those identified as being deterministic. The resulting timeseries is generated on an hourly basis with the total duration being equal to the simulation length specified.

2.3 Simulation of operations

Availability and other wind farm operational parameters can be calculated in the frequency domain through the combination of probability distributions for various situations. However, in practice, such calculations become unmanageable for all but the simplest case.

In order to overcome this limitation, a time domain Monte-Carlo approach has been adopted, which relies on random number generation to ensure that all possibilities are covered in an unbiased manner. Such an approach requires deterministic and stochastic events. While the former is governed by the inputs and assumptions outlined in Section 2.1, turbine failures and weather conditions comprise the stochastic elements of the simulation.

During simulation, each operational turbine is given the opportunity to fail at each timestep, which is nominally 1 hour. At this point, the model cycles through the failure mode schedule in a randomised order. For each failure mode a random number, R, between 0 and 1 is generated from a uniform distribution and compared to the MTBF (hours), for the failure mode in question. If the condition set out in expression (1) is satisfied[7], then the turbine in question is said to have failed in the current timestep, in the failure mode under test.

$$R < 1 - e^{-1/MTBF} \tag{1}$$

When a failure occurs, the turbine is shut down and a crew, if available, is allocated to perform the repair. If all crews are either occupied with repair operations or are not on duty, the turbine will remain down, and a crew will not be assigned until one becomes available for work.

When a crew becomes available and is assigned to conduct the repair work, that crew can only be deployed to the failed turbine if the current weather conditions (Hs and wind speed) are within the turbine access limits as defined in the model inputs. If these conditions are not met, the crew remains at their base and are only dispatched to the assigned turbine once the weather improves to within the access limits.

Given favourable weather conditions, the crew will be dispatched to their assigned turbine.

The time taken to repair the turbine once the crew are in attendance, is determined by the DTTR value specified for the fault in question. The model keeps track of the repair time remaining as the repair work progresses. Once the repair work is complete, the turbine is restarted and the crew either returns to base or goes on to any other turbine requiring repair or maintenance in the wind farm.

If during repair, weather conditions worsen to a level beyond the turbine access limits specified, repair operations are suspended and the crews return to base. In this instance, the turbine concerned remains inoperative.

However, the work already completed is logged so that the job can be continued when the turbine is next accessed.

Scheduled maintenance or servicing is implemented by the crews within the specified service interval, where possible. As mentioned previously, repair work takes precedence over scheduled maintenance, which is suspended if the crews are required for repairs. It is assumed that turbines can be restarted when servicing work is interrupted, with the service being completed when another crew becomes free and can access the turbine. Scheduled maintenance operations are also subject to weather delays in the same manner as those associated with repair work.

Clearly, there is scope for a wind farm O&M simulation in which crews cannot keep up with the specified scheduled maintenance requirements. In these cases, the assumption of a constant MTBF value for turbine faults throughout the simulation becomes unrealistic, invalidating the model outputs i.e. Turbines will fail more frequently if they are not serviced frequently enough. The model identifies if the maximum specified service interval has been exceeded for any of the turbines throughout the simulation and a view can then be taken on the validity of the model outputs for the simulation, given the frequency and severity of this exceedance.

The duration, in years, of the wind farm simulation is defined as an input. Given the stochastic nature of the model, it is preferable to initiate a long simulation to ensure that the outputs of interest are highly converged. The duration required to reach an acceptable level of convergence will vary depending on input assumptions, but for most scenarios, a simulation of 100 years has been found to be sufficient.

2.4 Post-processing and outputs

During the simulation, the O2M model records the status of each element of the wind farm at every timestep. In addition, key output variables of interest are recorded throughout the simulation, such as availability and lost production. The resulting operational database can then be queried to provide analyses of interest.

Figure 4 shows an example output plot of monthly averages of wind farm availability, accessibility and lost production for a sample 5 year period.

Notable in this example plot is the relationship between the three variables presented. The "high wind - low access" affect, as described previously, is clearly evident for two winter seasons in particular (years 2/3 and 4/5) as is the general inverse tendency in summer.

There are many output parameters that may be of interest for specific O&M investigations including spares usage and crew utilisation. For the purposes of the current study, such parameters are not explored here. The following sections provide a case study for a notional offshore wind farm whereby the long-term availability is estimated and the O&M resourcing is optimised.

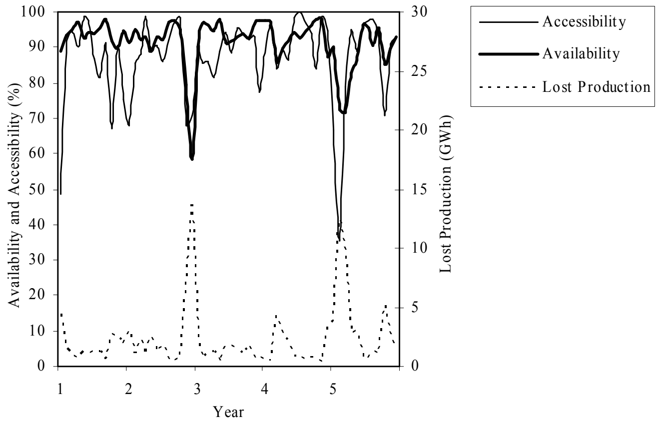

Figure 4: Example output plot of monthly averages of key operational parameters for a sample 5 year period

3. Estimating offshore availability

The notional offshore project, referred to henceforth as Wind Farm X, which has been used to demonstrate the modelling approach outlined in the previous sections, has a rated capacity of 300MW, consisting of 100 x 3 MW turbines. Some of the more important input variables are provided in Table 1.

Input parameter	Input assumption
Site parameters	
Long-term mean wind speed[1]	9.0 m/s
Long-term predicted cap. factor[2]	36 %
Mobilisation + transit time	2 hrs
Long-term Mean Sig. Wave Ht (m)	1.3 m
O&M resource parameters	
Access limit (Hs)	< 2.0 m
Access limit (wind speed)	< 15 m/s
Number of crews	6
Number of crews on shift 1	4
Number of crews on shift 2	2
Number of crews on shift 3	0
Number of technicians per crew	2
Crew working days / week[3]	5
Shift durations	8 hrs
Turbine reliability parameters	
Overall MTBF / turbine	1350 hrs
Mean repair hours / turbine / year	62 hrs
Mean lead time for jacking vessel	10 days
Scheduled maintenance frequency	6 months
Scheduled maintenance duration	16 hours

1. Predicted long-term mean wind speed at hub height
2. Capacity factor neglecting turbine downtime
3. One crew in every three works weekends

Table 1: Important input parameter assumptions for Wind Farm X

The MTBF assumptions used here are purely indicative and are presented above in summarised form. The indicative overall MTBF value assumed corresponds to an average of 6.5 faults per year per turbine. A discussion of the sensitivity of output variables to this assumption and how, in practice, such turbine reliability data could be attained is provided in Section 5.

A simulation was run for 100 years using the O2M model based on the assumptions presented in Table 1. The key outputs from this simulation are provided in Table 2.

Output parameter	Long-term Mean
Availability	92.4 %
Accessibility	80.6 %
Ideal Production[1] (GWh/annum)	955
Actual Production[2] (GWh/annum)	872
Lost Production[3] (GWh/annum)	83
Energy Availability[4]	91.3 %

1. Net production, not including turbine downtime
2. Net production, including turbine downtime
3. Production value of turbine downtime
4. Actual production as a fraction of ideal production

Table 2: Important output parameters for Wind Farm X

Despite the relatively harsh wave climate assumed at the Wind Farm X site, accessibility in excess of 80 % is achieved thanks to relatively aggressive wind and wave access limits. The resultant long-term availability of 92 % is poor when compared to industry expectations for an onshore project. Assuming that the turbine reliability is fixed, the most obvious way to improve the wind farm availability would be to increase O&M resourcing. However, without further investigation, it is unclear whether it would be economically desirable to do so. To address this point, an O&M optimisation exercise for Wind Farm X is described in Section 4.

The difference between Availability and Energy Availability is also worth exploring. Availability is simply defined as available fault-free turbine hours as a fraction of total turbine hours. Energy Availability is defined as the Actual Production as a fraction of Ideal Production. The reason that the value of these two parameters will always be different for offshore simulations of this nature, is that the distribution of turbine downtime against wind speed is non-uniform. In other words, the inherent correlation between wind speed and wave height means that poor availability is likely to coincide with windy periods.

4. Optimising offshore O&M

It is important to note the difference between the maximisation of wind farm availability and the *optimisation* of O&M strategies. Given that wind turbines are imperfect and will fail, 100% availability may (in theory) by achieved at an O&M cost tending to infinity. At the other end of the scale, with zero O&M investment, the long-term availability of the wind farm will be close to zero. In general terms, the situation is summarised graphically in Figure 5.

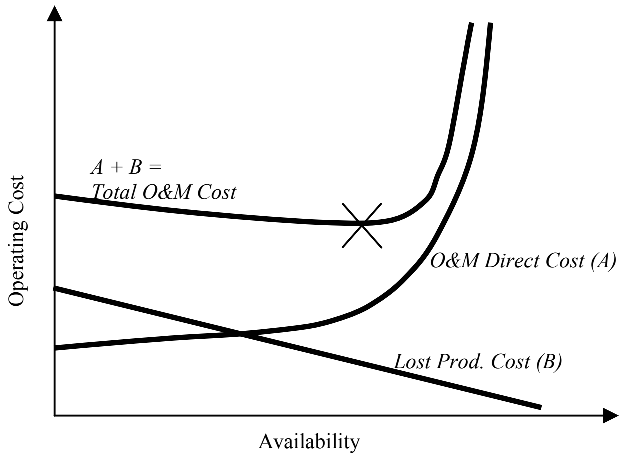

Figure 5: Indicative plot of wind farm O&M cost optimisation

In addition to the direct costs associated with O&M resources, the other major cost component of wind farm operation is that associated with lost revenues due to turbine downtime. The sum of these two cost sources provides the total cost of O&M, as illustrated in Figure 5. The indicative trends assumed in this figure for the two cost components yields a minima in total cost, denoted by the "x". This point is associated with the optimum O&M strategy for the wind farm and the most economic long-term availability level.

The O2M model can be used to estimate where the O&M cost optima lies for a given set of input assumptions. This is achieved through repeated wind farm simulation with a perturbation of O&M resourcing input parameters, for each run. Such an exercise is demonstrated in the following sections for Wind Farm X.

4.1 Optimising crewing strategy

The nominal staffing level assumed for Wind Farm X in the previous section was 6 crews. While other crewing variables such as shift and working days per week can be varied, for the purposes of the current study, the total number of crews has been investigated. Perturbations of multiples of 3 were used for crew numbers in order to preserve the consistency of the outputs in light of the non-uniform staffing rota.

Nominal assumptions for parts, labour and O&M infrastructure costs were assumed, based on industry knowledge. In commercial application, clearly these cost assumptions will need to be researched more thoroughly.

Figure 6 shows the results of this optimisation exercise. The data points on the curves represent individual model simulations each of 100 years duration. A clear cost minima is observed corresponding to a staffing level of 9 crews. Therefore, given that all other input parameters are fixed, this staffing level represents the optimum O&M strategy for Wind Farm X.

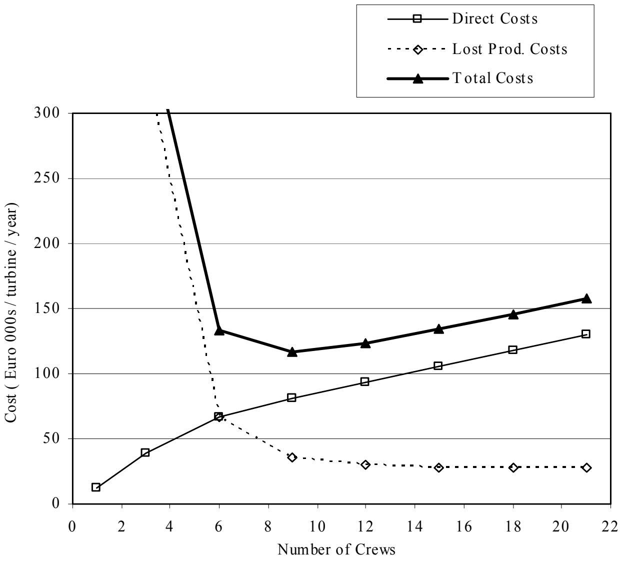

Figure 6: Wind Farm X cost optimisation, number of crews

For reference, a comparison of the headline results of the optimised and non-optimised (as in Section 3) Wind Farm X staffing configurations is provided in Table 3.

Output parameter	**Long-term Mean**	
	6 crews	**9 crews**
Availability	92.4 %	95.8%
Accessibility	80.6 %	80.6%
Ideal Production[1] (GWh/yr)	955	955
Actual Production[2] (GWh/yr)	872	911
Lost Production[3] (GWh/yr)	83	44
Energy Availability[4]	91.3 %	95.4%
Total O&M Cost (€ 000s / turb / yr)	133	116

1. Net production, not including turbine downtime
2. Net production, including turbine downtime
3. Production value of turbine downtime
4. Actual production as a fraction of ideal production

Table 3: Long-term mean output parameters for Wind Farm X employing 6 and 9 crews

This example shows that a relatively modest adjustment to O&M strategy can have a significant impact on overall operating costs. A similar approach can be taken to the other main element within an O&M strategy; turbine access method.

4.2 Optimising access method

There are several options open to offshore wind farm developers and O&M contractors when it comes to access method. Clearly, vessel choice is critical in determining safe access wind and wave limits, but there are various novel access methods on the market or under development that may improve these criteria. In addition, helicopter access, as has been employed at the Horns Rev offshore wind farm in Denmark[8], is also an option which might be considered under certain circumstances.

Two alternative access options have been evaluated for Wind Farm X, in addition to the current method which provides limits of < 2 m and < 15 m/s for Hs and wind speed, respectively. All three options are presented in Table 4 along with the assumed capital cost for each.

Access Method	**Hs lim.**	**Wind lim.**	**Capex**
A	< 1.5 m	< 15 m/s	€ 0.4 M
B[1]	< 2.0 m	< 15 m/s	€ 0.6 M
C	< 2.5 m	< 15 m/s	€ 1.2 M

1. Baseline access method for Wind Farm X

Table 4: Access options under consideration for Wind Farm X

The inter-dependent nature of staffing levels and access method means that the optimum number of crews derived in Section 4.1 is not necessarily an optimum for the two new access methods under consideration. Therefore, in order to find an overall optimum combination of staffing levels *and* access method, the crewing optimisation exercise has been repeated for access methods A and C. The results of this analysis are presented in Figure 7.

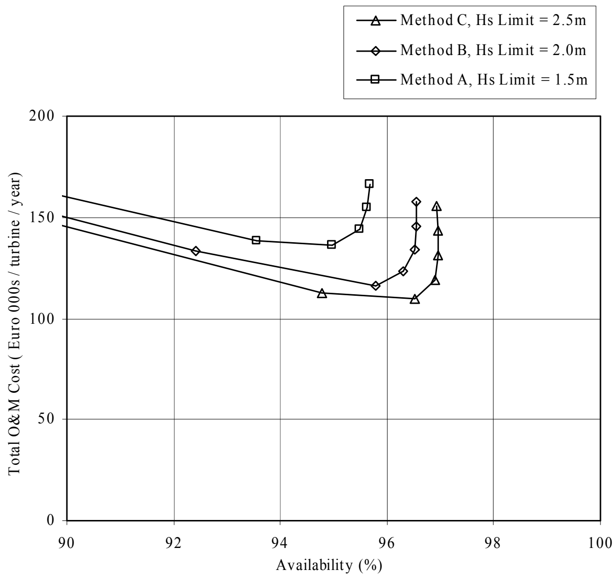

Figure 7: Wind Farm X cost optimisation, number of crews and access method

These results indicate that, for Wind Farm X, overall O&M costs can be reduced by a greater investment in the access method. Also of note is the steep increase in total operating cost after the optimum is reached. In crude terms, this indicates that increasing investment in O&M infrastructure, after a certain point, has very little impact on wind farm availability. It is important to note that it is not necessarily valid to apply these conclusions to other offshore wind farm projects, given the highly site-specific nature of many of the input variables.

Output parameter	**Access Method**		
	A	**B**	**C**
Optimum Availability	95.0 %	95.8 %	96.5 %
Accessibility	68.8 %	80.6 %	88.3%
Optimum No. Crews	12	9	9
Optimum Total O&M Cost (€ 000s / turb / annum)	136	116	110

Table 5: Output parameters for Wind Farm X, access method optimisation

Headline numerical results of the optimisation process are provided in Table 5.

These results indicate that with lower accessibility, as with Method A, more crews are required to reach the cost optima for Wind Farm X. In addition, although access Method C provides the lowest overall operating costs, the improvement from Method B is relatively slight. This suggests that there would be very little benefit in employing an even more expensive access method which achieves greater than 90 % accessibility.

5. Sensitivity to turbine reliability

Perhaps the most important of the input assumptions for any type of O&M simulation is that relating to turbine reliability. Failure rates and repair times are, of course, a very real and important consideration when selecting turbine models for wind projects.

In order to illustrate the variation of wind farm availability and total O&M costs with turbine reliability, a simple sensitivity study has been conducted for Wind Farm X. Using the input parameters for the optimised O&M strategy presented in the previous section, repeated 100 year simulations were run for variations in the overall MTBF assumption. The results of this exercise are presented in Figure 8.

The dotted circles in Figure 8 hi-light the simulation associated with the basic turbine reliability assumptions assumed for the optimisation exercises presented in previous sections. For this central case, the estimated long-term availability is 96.5% with an associated total O&M cost of € 110,000 per turbine per annum.

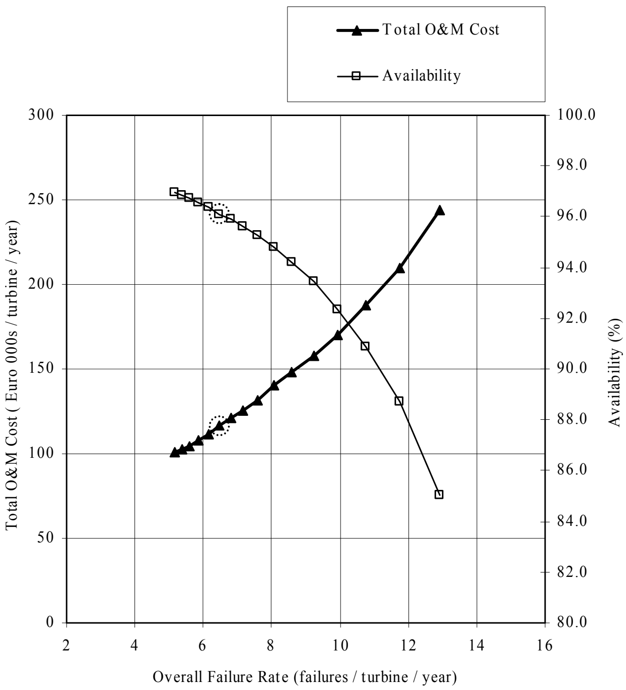

Figure 8: Turbine reliability sensitivity study for Wind Farm X

Although not the result of an extensive investigation into turbine reliability, the range of failure rates assumed for the sensitivity study might be considered a first approximation of optimistic and pessimistic reliability scenarios for a wind farm. An important observation from Figure 8 is that, for a fixed perturbation in either direction from the central case, the optimistic assumption provides less benefit than the detriment incurred by a pessimistic assumption. In other words, the upside is not as good as the downside is bad.

Figure 8 also shows the magnitude of wind farm performance sensitivity to turbine reliability. Doubling the failure rate from 6 to 12 failures per turbine per year almost exactly doubles the projected overall O&M costs for Wind Farm X.

The results of this sensitivity study show that an O&M simulation of this kind should be accompanied by a detailed investigation of turbine reliability. Such an investigation can be based on published turbine reliability statistics, propriety operational data from other wind farms in an owner's portfolio or generic industry knowledge. However, perhaps the best source of reliability data is the turbine manufacturers themselves. Analyses such as the sensitivity study presented in Figure 7 may be sent to potential contractors and discussions held with them over the long-term central and "downside" failure rate assumptions for particular turbine models.

6. Conclusions

The contrast between the operation of onshore and offshore wind farms is potentially very large. In the onshore case, decades of operational experience has allowed a good understanding of the risks associated with long-term energy estimates to be developed. In addition, this experience has provided a reasonably reliable "rule of thumb" for long-term wind farm availability of approximately 97%.

Clearly, the issue of access is substantially more important for offshore wind farms given the inevitable delays introduced by adverse sea conditions. Also, the cost of repair and maintenance work offshore is anticipated to be more variable because of the specialised equipment required for certain operations. The combination of these two factors along with a general lack of commercial experience, presents the offshore wind industry with significant operational uncertainty. O&M risks should be analysed, understood and managed appropriately. To support this process, a simulation modelling approach has been developed.

The model, known as O2M, is based on time domain Monte-Carlo simulation with turbine failures and weather conditions being stochastic variables. Deterministic variables comprise model inputs and underlying behavioural assumptions. Operational simulations can be run for many years during which all performance parameters are recorded. Various analyses can then be applied to the model output database.

The O2M model has been applied to a notional offshore wind farm in order to demonstrate how long-term availability and other important operational performance parameters can be estimated. Repeated simulations have implemented to show how both staffing levels and turbine access method can be optimised for a given project. Finally, the sensitivity of wind farm performance and O&M costs to turbine reliability has been investigated.

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